DEPARTMENT OF THE INTERIOR, CANADA

HONOURABLE THOMAS G. MURPHY, Minister

TOPOGRAPHICAL SURVEY

BULLETIN No. 63

THE ANEROID BAROMETER AND ALTIMETER

OTTAWA
F. A. ACLAND
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1931

Price, 10 cents

SURVEYOR READING SET OF THREE FIELD BAROMETERS

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THE ANEROID BAROMETER AND ALTIMETER

THEIR CHARACTERISTICS AND USE IN MAPPING

BY

R. H. FIELD

SUPERVISOR, PHYSICAL TESTING LABORATORY,

WITH AN APPENDIX

THE FIELD USE OF THE ANEROID BAROMETER

BY

G. C. COWPER

DOMINION LAND SURVEYOR

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FOREWORD

In connection with its national mapping program the Topographical Survey, Department of the Interior, has before it the problem of covering with map sheets large, hitherto unmapped areas. In this problem, considerations of economy make it necessary to adopt for this purpose, instruments which will permit the required topographic detail to be rapidly mapped at a minimum of cost. The aneroid barometer, as an instrument for use in connection with topographic mapping, has hitherto been indifferently received by most surveying organizations throughout the world. However, for the scale and contour interval required and the conditions prevailing in the Dominion it has been found possible to employ the aneroid barometer upon this work.

A certain amount of investigation both in the Physical Testing Laboratory and in the field was required before the best use could be made of the instrument. This bulletin contains a resumé of the most important results of the laboratory investigations, together with a short description of the instrument itself, by R. H. Field, Supervisor of the Physical Testing Laboratory; and an appendix by G. C. Cowper, D.L.S., describing field methods successfully employed in the actual mapping operations.

F. H. PETERS,
Surveyor General.

OTTAWA, CANADA,
October, 1930.

CONTENTS

APPENDIX

The Aneroid Barometer and Altimeter

INTRODUCTION

The aneroid barometer has been extensively used on surveys by the Topographical Survey, Department of the Interior, for many years. In the development of the use of the instrument a considerable amount of investigational work was undertaken, both in the field and by the Physical Testing Laboratory. It was found, very early in the operations, that there was little published information available, and even then a large proportion of the existing material was misleading or directly contradictory to fact. In many cases the instrument was summarily dismissed as inaccurate and wholly unreliable, which was possibly quite true as regards the particular specimens which fell into the hands of the writers concerned.

The results of the laboratory work may be embodied in the following conclusions:—

(*a*) There was room for considerable improvement in the performance of most aneroid barometers, but they could be rendered much more accurate and reliable for surveying purposes by fairly simple means and without altering the design too radically.

(*b*) Most aneroid barometers, if purchased indiscriminately, were likely to be found to have errors which precluded the use of the instruments for any but the roughest operations.

(*c*) As a result of (*b*) it is necessary to purchase surveying aneroids to specification and to subject them to a laboratory test before issue for field work.

(*d*) Barometers in use should be examined in the laboratory annually to detect the acquisition of errors, which can then be corrected.

The present bulletin contains a short description of the mechanism of the aneroid barometer and its characteristics as well as the modifications of the instrument when it is employed as an altimeter to indicate the height of aircraft, a short summary of the atmospheric data upon which rests the application of the barometer or altimeter to elevation measurements, a reproduction of the standard specifications of the Topographical Survey for surveying aneroid barometers, and an appendix on the field use of the aneroid barometer.

THE MECHANISM OF THE ORDINARY PATTERN ANEROID BAROMETER

Historical.—The aneroid barometer was originally invented to measure altitudes in the early days of balloon ascents. In very much the same form the instrument persists to-day as one of the most important used on aeroplanes, where it is called an "altimeter." Although modifications of the mechanism have been made, most of the best aneroids of to-day in practical use, while improved as to materials, workmanship and details of design, are substantially the same in appearance as those used fifty or sixty years ago. Several attempts have been made with more or less success to introduce mechanisms designed on improved principles, but so far none of these has been free from all objections when considered from the surveying or aeronautical point of view, and the simple, orthodox instrument is still by far the most widely favoured.

Description.—In the mercurial barometer the pressure of the atmosphere is measured by the height of the column of mercury under standard conditions, which it will support. The aneroid barometer measures this same pressure by means of a spring, the deflection of which is indicated by a suitable mechanism.

Fig. 1 is a drawing of the usual type of mechanism found in aneroid barometers. The atmospheric pressure acts on a sealed capsule *A* which is generally exhausted to a few millimetres pressure. The capsule is corrugated

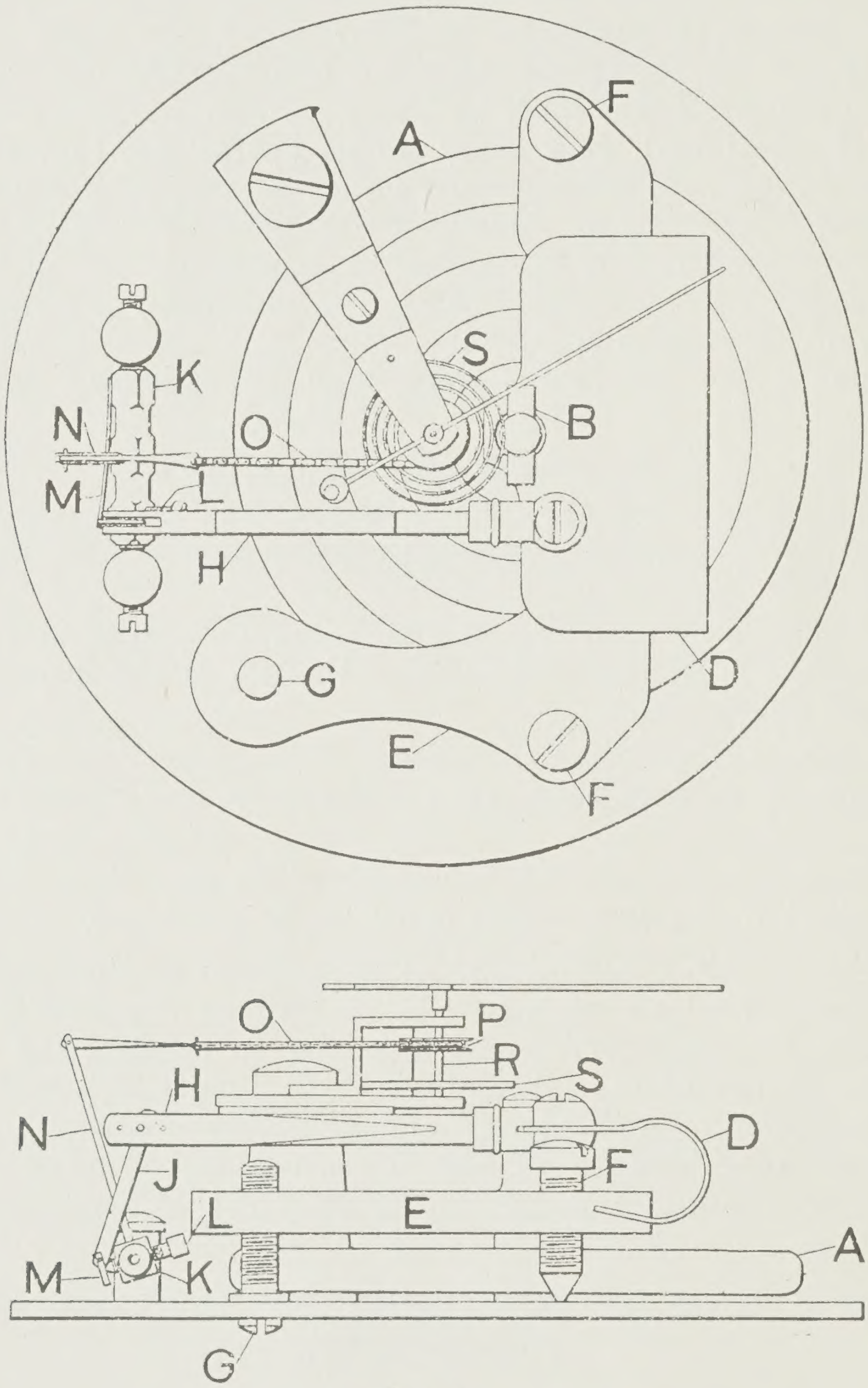

Fig. 1

PLAN AND ELEVATION OF THE MECHANISM OF THE ORDINARY ANEROID BAROMETER

A, Exhausted capsule; B, Knife edge; D, Main Spring; E, Carriage; F, Supporting screw; G, Adjusting screw; H, Bi-metallic lever; J, Link; K, Regulator spindle; L, Regulating screw; M, Regulator spring; N, Lever; O, Chain; P, Chain pulley; R, Hand arbor; S, Hair-spring.

to give local stiffness and has flanged stems at the centre of its top and bottom diaphragms. The lower stem is attached to the base of the mechanism while the upper one carries a knife-edge *B* which rests on the top of the measuring

spring D of C form. A carriage E supported by three screws, carries the other arm of the spring. The two screws F are pointed, and located so that the line joining them passes near the centre of the capsule stem. By turning these screws the carriage is raised or lowered as desired in order that the mechanism can be suitably adjusted. The pressure on the third screw G is relatively small, and this screw, generally operated from outside the case of the instrument, serves to make small adjustments to the position of the indicating hand by tilting the carriage.

An arm H, rigidly attached to the spring, deflects through an angle as the spring moves in response to changes in the pressure on the capsule. The free end of the arm H is connected by a link J to a spindle K, which rotates as H rises or falls. The angular velocity ratio between H and K can be altered by the screw L which bears against a flat spring M, to the free end of which the link J is attached by a small hinge pin. This permits the magnification ratio of the mechanism to be adjusted.

A lever N on the spindle K is pinned to a fine chain O, the other end of which is attached to the pulley P, round which it winds as the lever N approaches. The pulley is tightly held on an arbor R and a hairspring S is also colletted to the arbor so as to cause the chain to be under tension at all times. The hand of the instrument fits on the arbor and moves over a graduated dial.

A photograph of the mechanism is reproduced in Fig. 2.

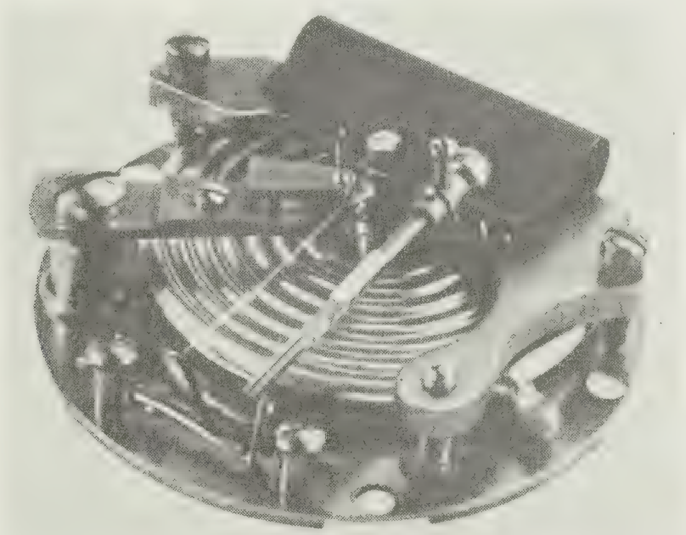

Fig. 2

THE MECHANISM OF THE ANEROID BAROMETER

The parts shown in Fig. 1 can all be seen in this illustration. In the latest pattern D.L.S. surveying aneroid changes have been made from this form of mechanism, which does not give the highest accuracy in surveys.

A pressure change corresponding to 0·01 inch of mercury is approximately equivalent to 0·005 pound per square inch. It will thus be seen that, as it is desirable for aneroids to be sensitive to pressure changes of this order or less, the mechanism must be very carefully constructed. Moreover, the magnification ratio between the vertical displacement of the knife-edge and the movement of the hand over the graduations is usually two or three hundred, and this fact also necessitates good workmanship if it is desired to avoid errors comparable in magnitude with the changes in the quantities being measured.

ERRORS OF THE ANEROID BAROMETER

Thermal Errors.—As the aneroid barometer is constructed entirely of metal, changes of temperature, as might be expected, have an appreciable effect upon the indications unless compensated by the introduction of some device designed for the purpose. It should also be remembered that when an aneroid is subjected to a temperature different from that to which it was previously exposed, sufficient time must be allowed to elapse before readings are taken, as until all parts are at a uniform temperature, it cannot be certain that the reading is not subject to large errors. This period of thermal " soaking " varies with different types of instruments, but in some instances the thermal error of an aneroid a short time after exposure to a new temperature may be quite large compared with the final error due to the change.

By properly selecting materials the temperature errors in the links, levers, chain, etc., of the mechanism can be reduced to negligible proportions, leaving most of the residual effect to originate in the spring. If we neglect the elastic effect of the capsule itself, the load upon the spring can be taken as the pressure exerted by the atmosphere, which tends to collapse the capsule.

If the further assumptions be made that

(1) the deflection of the spring varies directly as the load upon it,

(2) the change in the modulus of elasticity of the spring material with temperature follows a linear law,

the change in deflection at any pressure, for the same change in temperature, will be directly proportional to the pressure.

Compensation.—It is stated that the first method employed for compensating aneroid barometers was to leave a certain amount of air confined in the capsule. This air expands with increasing temperature exerting a pressure within the capsule which acts in the opposite direction to the atmospheric pressure and so reduces the load on the spring. If the effect of the small changes that take place in the volume of the capsule be disregarded, the change in pressure, and therefore of spring deflection, due to thermal changes in the residual air will be independent of the pressure, and therefore cannot compensate the changes in the spring deflections at all pressures, under the conditions assumed. By varying the amount of the residual air, however, it is possible to achieve good compensation at any given pressure.

The more usual method at the present day is to make the lever *H*, Fig. 1, of bimetallic form. Usually the body of the lever is brass with a steel or invar strip soldered to the top. The effect of temperature changes is to vary the curvature of the arm and so introduce a movement of the hand which is independent of spring deflections. The introduction of the bimetallic lever produces similar effects to that obtained by leaving residual air in the capsule. By changing the amount of steel on the arm it is possible to compensate an aneroid at any desired pressure. This is a more satisfactory way, from a practical point of view, than changing the amount of air in the capsule, as, once the capsule is sealed, its airtightness is not disturbed.

If a typical aneroid barometer, compensated by one of these methods, be compared over its range at, say, three different temperatures, with the mercury standard, and the corrections plotted against readings, curves such as those in Fig. 3 will be obtained.

It will be noticed that the three curves are more or less similar in form but that the slopes increase with rise of temperature, i.e. at higher temperatures an indicated pressure change of one inch of mercury corresponds to a smaller real change than at lower temperatures. Also, it will be noticed that the curves tend to cross at a common point, corresponding to a pressure (about 27 inches)

at which almost perfect compensation for temperature is effected. In general by altering the composition of the bimetallic lever or the amount of air within the capsule it is possible to change this pressure. By this means aneroids can be compensated at the pressure at which they are most generally used, thermal errors at neighbouring pressures being a minimum.

Compensation of Altimeters.—It is not probable that the deflection of the knife-edge on the top of the spring in commercial aneroids is linear in regard to pressure, but a more or less perfect degree of compensation for thermal errors can be obtained in altimeters by fitting a device to give an angular movement to the hand with change of temperature which is independent of pressure.

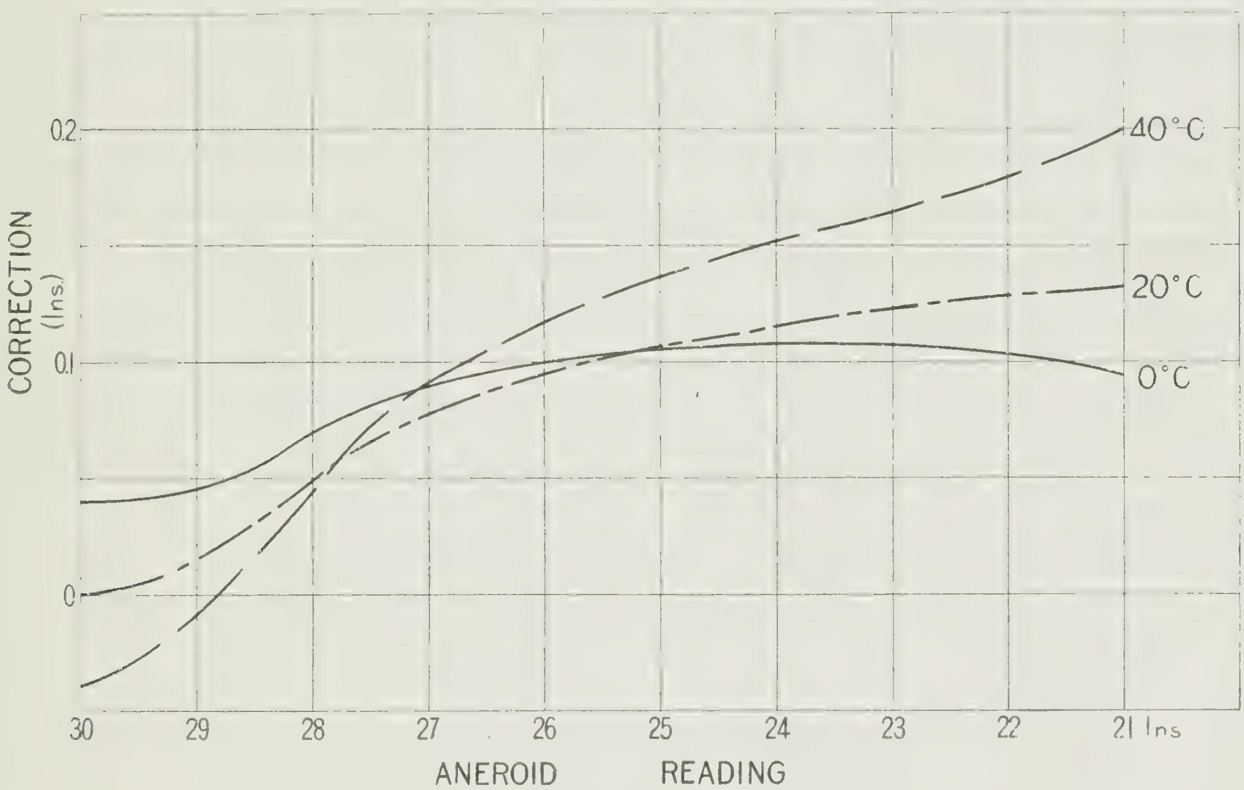

FIG. 3

CALIBRATION CURVES FOR AN ANEROID BAROMETER

The three graphs show the calibration corrections at 0°C, 20°C, and 40°C, respectively. The zone of compensation, where temperature has little effect on the readings, can be clearly seen. By making this zone come at the usual working pressure, thermal errors can be reduced to negligible proportions for most purposes. When the instrument is used over its whole range, minimum errors occur when it is compensated at the centre point of the range.

The theory of compensation devices of this nature depends on the relation between atmospheric pressure and height which is employed in graduating altimeter dials (page 22). The formula is such* that at any height (or pressure) the change in pressure corresponding to the same change in altitude is directly proportional to the pressure in question. As these dials are usually graduated so that equal increments of height subtend equal angles the thermal error under discussion should give rise to an error of reading, the amount of which is independent of the reading itself, and can therefore be compensated in the manner mentioned.

* The formula is of the form:

$$H = K \log P.$$

where:— H=The height
P=The corresponding pressure.
K=A constant.

This when differentiated takes the form:—

$$dP = PdH.$$

In the British Air Ministry Mark VII altimeter, the spring is relatively long and also supported at the bottom by means of a knife-edge. A bimetallic helix connects the hand to the arbor, and the instrument shows remarkably good thermal compensation. Similarly in the British Mark 1 altigraph, compensation is achieved by a bimetallic strip giving a deflection of the pen arm independent of the reading.

In an experimental aneroid constructed at the Physical Testing Laboratory after the usual commercial pattern, a small bimetallic leaf was attached at one end to the spring *M*, Fig. 1, and the link, instead of being fastened to the spring itself, was attached to the free end of the leaf. The effect then was that with rise of temperature the leaf bent and reduced the effective leverage acting on the spindle. By this means the curves shown in Fig. 3 were rendered practically parallel, and then the regular bimetallic compensation was adjusted until the thermal error was extremely small throughout the range of the instrument.

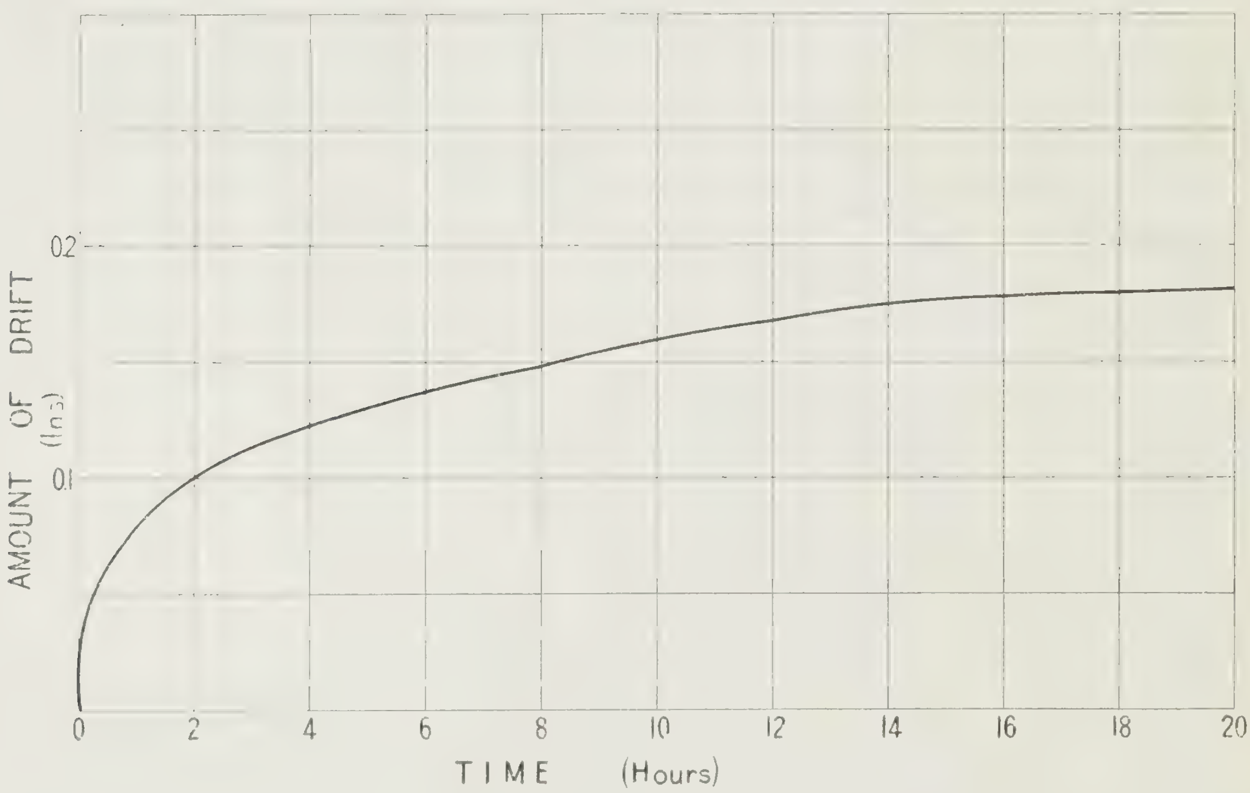

FIG. 4

CURVE SHOWING THE GROWTH OF "DRIFT" OR "CREEP"

This curve is typical; the ordinate will vary with the amount of pressure change preceding and giving rise to the drift. This characteristic caused much trouble to mountaineers and others in bygone years, who attempted to measure mountain heights with aneroid barometers. With modern instruments the amount of drift or creep is very small, and sometimes negligible for most purposes.

Various other devices have been used by different makers and these together with improved design and selection of materials have resulted in compensation being now obtained in good instruments to a degree unheard of ten years ago.

As a rule aneroids marked "Compensated" on the dial are fitted with the ordinary bimetallic lever and are strictly compensated at one pressure only, which may or may not be a convenient one from the point of view of the user.

One cause of extreme thermal errors at higher temperatures which, however, is not likely to occur in the products of well established makers, is moisture being allowed to remain inside the capsule, the increased vapour tension at rising temperature producing considerable errors in the indications of the aneroid.

In new instruments the thermal errors are not always reversible, when the aneroids are subjected to a cycle of temperature changes. This has been found to be due to strains set up in soldering the bimetallic lever, and can be removed by heating to the temperature of boiling water for a time—giving an annealing effect.

Drift.—One of the most troublesome characteristics of aneroid barometers, particularly where large pressure differences are involved, as in mountaineering or aviation, is drift or creep. Its existence has long been known, and while its characteristics have been studied by Chree,[1] Whymper [2] and others, it is only in recent years that its magnitude has been appreciably reduced.

If an aneroid which has been standing for some days at atmospheric pressure, be subjected to a lower pressure, and be then compared periodically with the mercury barometer, the graph of the correction, plotted to a time base, will be like that shown in Figure 4.

The magnitude of the ordinate will vary with the instrument, but aneroids have been tested at the Physical Testing Laboratory and found to accumulate a drift of as much as 0·4 inch in twelve hours under a pressure 10 inches less than atmospheric.

A somewhat similar effect will be noticed if an aneroid is subjected to a reduced pressure and then allowed to return to atmospheric pressure. When first read, after the return, it will be found, as a rule, that the instrument has acquired a different correction, and some time, depending on the drop in pressure and other factors, will be required before the original correction at atmospheric pressure is regained.

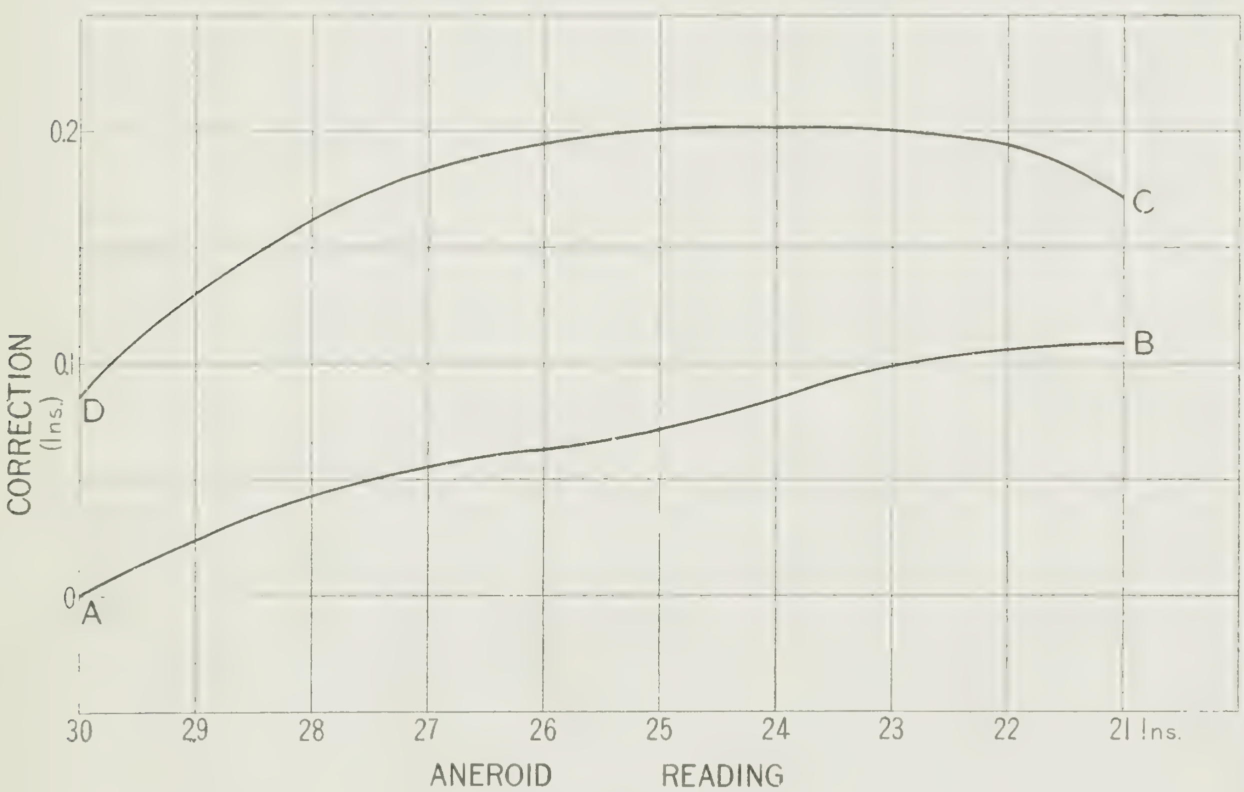

FIG. 5

CALIBRATION CURVES, INCREASING AND DECREASING PRESSURES WITH DELAYED RETURN

A period of five hours, during which the aneroid remained under a pressure of 21 inches of mercury, elapsed between the readings giving rise to these two graphs. The effect of drift and hysteresis is shown by the separation between the two curves. Had the return to atmospheric pressure been made immediately the 21-inch pressure was reached, the separation between the two corrections at each reading point would have been smaller.

[1] Phil. Trans. Royal Society, Vol. 191 (1898) pp 441-449.
[2] "How to use the Aneroid Barometer," by Edward Whymper.

These and allied effects, referred to as drift, creep, hysteresis, after effects etc. are elastic in nature and are due to the capsule and to a less extent the spring and other parts not being perfectly elastic in the sense usually understood and responding instantaneously and completely to a change of stress. They are also due to "give" in the spring supports and parts under varying loads.

If the pressure to which an aneroid barometer is subjected be reduced, and comparisons with the mercury barometer be made at each inch point, a curve of corrections such as *A B*, Fig. 5, will be obtained. If now the aneroid be allowed to remain at the low pressure (21 inches of mercury in the example) for, say, five hours, the correction to the mercury barometer will be found to have changed from the point *B* to the point *C* during the interval, as illustrated in Fig. 4. On bringing the aneroid back to atmospheric pressure, and comparing with the mercury standard as before, a curve of corrections such as *C D* will be obtained, the correction at atmospheric pressure having changed by the amount *A D*. In the course of several hours, this correction will return to its original amount, in the case of good aneroids.

One of the chief sources of drift, which for long was unsuspected, was found in the solder uniting the edges of the top and bottom diaphragms forming the capsule. Older instruments were made with lap joints (Fig. 6A), containing a relatively large amount of solder. By using a flanged joint, (Fig. 6B), with practically no solder, or by welding, the amount of drift was reduced by one-half or more. All good aneroids now have flanged joints for the capsule.

Fig. 6

OLD AND NEW STYLE OF CAPSULE JOINT

A.—Old style of capsule joint, showing soldered lap joint.
B.—New style of capsule joint in which little or no solder is used.
Drift has been considerably reduced by the adoption of this latter type of joint which is now employed by all high class aneroid barometer and altimeter manufacturers.

By suitably selecting and treating the capsule and spring material and by mounting the spring very firmly in the carriage or on knife-edges still further improvements have been attained, and it has been possible to produce aneroids with only a one-fiftieth part of the drift found in older types.[1]

Secular Changes.—Closely allied with drift and probably due to similar elastic and mechanical effects, are the secular changes that take place in the indications of an aneroid barometer when held for a prolonged period at a constant pressure. This characteristic, which is found more or less in all instruments depending on the deflection of springs or other elastic deformations, makes it risky to rely for long periods upon the indications of an aneroid barometer if used for absolute measurements of barometric pressure. It is not likely to cause much trouble to the surveyor except on prolonged reconnaissance or allied work where it is impossible to tie up to known elevations or where data are not available for checking the corrections of the aneroid from time to time against a mercury barometer or known pressure.

The general experience of the Physical Testing Laboratory tends to show that aneroids with small drift errors are less likely to be subject to secular errors.

[1]Stewart, Journal of the Royal Aeronautical Society June, 1928, page 429.

In one sample instrument tested by the laboratory, which had extremely small drift, (about 25 per cent of that found in the usual type of instrument up till quite recently) no appreciable change in the correction at atmospheric pressure could be detected over a period of some two months, although, during this interval, the instrument was subjected to various tests involving large temperature and pressure changes. If instruments as good as this can be duplicated they should be valuable for measuring the true atmospheric pressure at sea or elsewhere when the use of a mercury barometer is impracticable.

Sensitivity and Mechanical Errors.—From the point of view of the mapping engineer, who is usually anxious to measure small elevation differences, lack of sensitivity and changes in the indications due to mechanical errors, are of extreme importance. An aneroid barometer may be constructed practically free from drift and allied errors and be well compensated against temperature changes, yet if tapping the instrument will cause the hand to take up any position over a range equivalent to fifty feet or more, or if a blow, such as may easily be given in traversing rough country, will cause the hand to move to a new position, 100 feet or more from its original reading, it can readily be seen why a surveyor may discard the instrument in disgust.

Yet the figures cited above are by no means uncommon in the case of surveying aneroids sent for test or repair to the Physical Testing Laboratory and their cause can nearly always be traced to simple defects. One defect for which the demands of the surveyors themselves are probably in a large part responsible, is the attempt to enclose the mechanism in a " watch " type case. With the design of mechanism usually adopted, the component parts are too small to produce a satisfactory aneroid for surveying purposes in these "watch" cases. The Topographical Survey of Canada has found that from all points of view, the most efficient size of aneroid is one with a case of $2\frac{3}{4}$ inches to 3 inches diameter and about $1\frac{1}{4}$ inches deep. This gives a readable, serviceable instrument, large enough to permit of sufficiently robust mechanism and yet not too massive or bulky for portability.

But even in larger aneroids the errors mentioned are frequently found and are the cause of a great deal of trouble.

For convenience the Physical Testing Laboratory divides these errors into two classes. Lack of sensitivity such as is evidenced by tapping the instrument and noting the range over which the hand comes to rest during a series of taps, is referred to as the " tapping error." Movement of the hand produced by a blow—such as that given when the aneroid is held in one hand and then struck with some force against the palm of the other—is called the " shift error." To differentiate between the tests, the aneroid should be lightly tapped after each blow of the " shift " test so that true shift will be observed.

" Tapping " errors are due to looseness in the joints between the links and levers, poor fit of spindles and similar defects or on the other hand to excessive friction, defects in the chain or the hairspring. These errors are readily avoided if good workmanship is put into the mechanism and, provided the details of design are good, their reduction to a reasonable figure does not necessitate any radical change in the usual type of aneroid.

" Shift " errors are usually due to looseness in the supporting members of the mechanism, movement of the knife-edge relative to the spring or other defects which cause the indicating mechanism to take up a different position as the result of shock. It may even be due to a loose fit of the dial in the case of the instrument.

Looseness in the carriage-supporting screws and poor location of the knife-edge are usually the main sources of shift errors. Frequently the error can be considerably reduced by refitting the carriage-supporting screws, both in the thread where they pass through the carriage and at the points located in

centres or vees on the base plate in the case of the two fixed screws. Further stability can be given to the carriage by fitting locknuts to these screws, so that when the carriage is correctly located, the nuts can be tightened and the rigidity of the supports increased. The adjusting screw may also contribute to the error, and it should bed nicely down to the base plate.

The knife-edge should be definitely located in a fine groove cut in the spring. It should also be firmly held in the stem of the capsule and be stiff enough to prevent its becoming seriously deformed under load.

Owing to the difficulty in eliminating shift errors from the usual type of aneroid barometer, the Topographical Survey of Canada specifies for new instruments that the spring carriage must be rigidly supported, and the three screw method is not acceptable. In recent aneroids purchased, the spring carriage is supported on two blocks, adjustment in assembly being obtained by

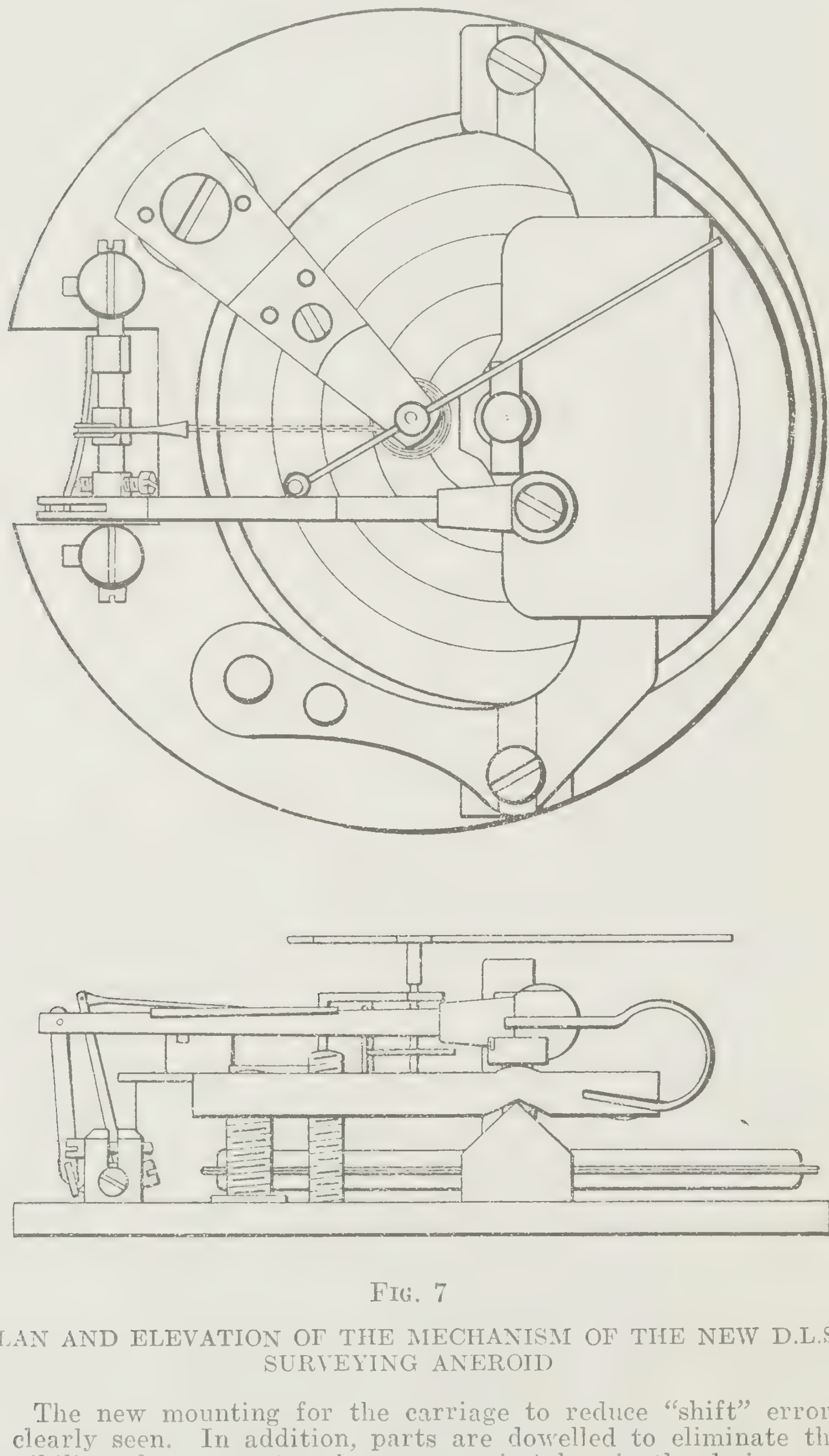

Fig. 7

PLAN AND ELEVATION OF THE MECHANISM OF THE NEW D.L.S. SURVEYING ANEROID

The new mounting for the carriage to reduce "shift" errors is clearly seen. In addition, parts are dowelled to eliminate the possibility of movement and more care is taken in the design and fitting of the pivots, links, etc. A comparison with Fig. 1 will reveal these and other differences.

the use of two nuts on the lower stem of the capsule, one above the base plate and one below. In place of a single adjusting screw these aneroids have a pair of antagonistic screws, so that after adjustment of the hand the screws can be tightened, and the carriage held rigidly.

As the movement of the knife-edge is magnified some two hundred or more times at the end of the hand, it can readily be seen why movement of the carriage or knife-edge is of such serious importance as a cause of shift errors.

Other Mechanical Defects.—Besides the defects present in new instruments, treated above, other sources of error may develop in aneroid barometers in the course of service. Rust may occur and on such parts as the chain or hairspring the consequences, as affecting the precision, may be serious. Quite frequently, in old aneroids, one or two links of the chain may be stiffened up from this cause, introducing a peculiar form into the plotted graph representing the corrections throughout the range of the instrument. Some authorities prohibit the use of steel in the hairspring or chain. Phosphor bronze is then usual for the former and nickel for the latter. Hairsprings also lose their resilience or original form, and heavy jars may even dislodge the knife-edge or the carriage-supporting screws. Consequently, the Topographical Survey of Canada has adopted the policy of carefully examining all surveying aneroids each year, at the end of the field season, to ensure that they are kept in good condition.

The surveyor should be warned against attempting to adjust the hand of an aneroid over more then one or two tenths of an inch by means of the adjusting screw or screws at the bottom of the case. As can be seen from Figure 1, this screw acts by tilting the spring carriage and hence the spring and the arm. If the screw be turned until the arm moves downwards through a sufficient angle, the chain will unwind completely off the drum and further movement will snap the chain. Quite frequently aneroid barometers with chains broken from this cause are received at the Physical Testing Laboratory for repair. If the hand develops a considerable error some defect has occurred to the mechanism and it is safer to return the instrument for repair without attempting to adjust it, as in any case excessive movement of the hand by means of the adjusting screw may affect the calibration errors of the aneroid.

Errors due to lack of balance in the mechanism can be avoided by always reading the instrument in one position.

Modifications of the Usual Type of Mechanism.—Aneroids have been built from time to time with micrometric devices for measuring the deflection of the spring required to balance the load on the capsule. Many years ago this was done in the Goldschmidt aneroid. At each reading a micrometer screw was turned until it was exerting a small but always equal pressure on the spring. The reading of the micrometer then, was a measure of the deflection of the spring and hence of the load acting upon it.

In a later form of micrometer aneroid the top of the capsule is drawn out to the same position at each reading. The standard position is indicated by a special indicating mechanism and pointer, and the micrometer screw, which distends the upper end of a helical spring, (the lower end being attached to the capsule) measures the pull needed to distend the capsule to that position. This type of aneroid is very sensitive and as a rule is much more accurate than the usual sample of standard instrument, except those of recent construction. It suffers from certain defects, however, and from the mechanical point of view, is somewhat frail and easily deranged. Moreover each time the capsule is distended when taking a reading, a drift effect takes place and if readings be taken at short intervals while the instrument is under a constant pressure a small but progressive variation will be found.

It has been demonstrated by actual trial that direct reading aneroids of robust construction, like that illustrated in Fig. 7 can be built sensitive enough for measuring atmospheric pressures to be used in height determinations—to which there is a limiting precision owing to various local and accidental atmospheric disturbances. As this type of aneroid is eminently more suited for surveying operations it has been adopted by the Topographical Survey of Canada.

In a special aneroid submitted to the Physical Testing Laboratory by a well known British firm, the external spring was omitted. A series of capsules was used, and they were stiff enough that no additional spring was required. The deflection of the end diaphragm of the system was communicated directly by links and levers to the hand through the usual chain and pulley. This aneroid had very small errors, suggesting that the type might well be developed. From the surveying point of view its main draw-back was the price, which was considerably in excess of that for which satisfactory instruments of the older pattern can be purchased.

THE ALTIMETER

The altimeter is an aneroid barometer mechanism with the dial graduated to indicate elevations directly. In practice (see page 22) it is impossible to construct an instrument that will indicate at all times the true height from a single measurement of the atmospheric pressure. Various approximations are adopted, however, which permit the altimeter dial to be graduated so as to indicate the elevation of the instrument with more or less error. In accurate determinations of altitude from barometric measurements, the only method available is to find the true pressure at the upper and zero limits of the altitude in question and apply the necessary corrections to standard formulæ.

In the usual altimeter, as fitted to aeroplanes, the tapping and shift errors are not as important as in surveying aneroids. The drift and thermal errors, however, should be small as the instruments are used over much wider pressure and temperature ranges than those usually encountered in terrestrial work.

Altimeters are generally fitted with dials marked with every one thousand foot interval subtending the same angle. The dials are made rotatable so that at the commencement of a flight the instrument can be set to read zero or the elevation of the ground at the start of the flight. In some modern instruments an auxiliary fixed scale reading in inches of mercury is fitted (see page 27).

RECORDING ANEROID BAROMETERS

In most modifications of the aneroid barometer to serve as a recording instrument, a battery of several capsules is employed, to give a smaller magnification and consequently a larger force acting at the indicating point where there is usually some friction against the chart. External springs are unusual in recording aneroids, which are generally provided with a helical spring inside the capsule system.

The general form of chart is that placed on a cylindrical drum, rotated by a clock. For aeronautical purposes, where the range of pressure is relatively great, the scale is small, but one well-known American firm has overcome this difficulty by arranging the linkage system so that the pen point traverses the paper four times, alternately up and down, when the instrument is subjected to a pressure change corresponding to its total range.

For use as a fixed instrument, to determine atmospheric changes at a selected station while elevations are being measured by means of aneroid baro-

meters at other stations in the vicinity, the barograph possesses some advantages. As in the case of the aneroid itself, however, care must be taken to provide a good instrument of proven characteristics, otherwise errors are likely to give trouble.

In a special barograph designed for the Geodetic Survey of Canada and containing several unique features, the scale of the instrument covered a range of only one inch of mercury, on a chart four inches wide. The range of the instrument could be adjusted so as to cover any inch between 25 inches and 31 inches of mercury. This particular barograph had a single large capsule and C spring as in the ordinary aneroid barometer. The sole magnifying medium was a "bryony," consisting of a small thin-walled bronze tube about one-eighth of an inch in diameter and slit in a right-hand helix of quick pitch from one end to near the centre and in a left-hand helix from the other end towards the centre. If the bryony be held at the ends and stretched, the solid portion at the centre will rotate. In this barograph the pen arm was fastened to the centre of the bryony and movements of the spring thus caused it to move over the face of the chart. A chopper bar, of the type used on sensitive recording galvanometers, pressed the pen against the paper every half minute, and at other times the pen arm swung freely, thus eliminating friction. This instrument was remarkably accurate. Besides being almost free from thermal and elastic errors, it was so sensitive that it would show tremors in the atmospheric pressure of the order of 0·001 inch or less, which are entirely masked in less precise barographs. The pen arm, if watched under appropriate atmospheric conditions, could often be seen to oscillate through a small angle, due to minute pressure changes which reference to the mercury barometer showed to be actually taking place.

ADJUSTMENT AND TEST OF ANEROID BAROMETERS AND ALTIMETERS

Adjustment of the Regular Pattern Instrument.—It is impracticable by calculation to design an aneroid barometer so that it will indicate atmospheric pressure changes correctly. Consequently each instrument has to be adjusted to read as nearly as possible the same as a standard mercury barometer covering a like range.

In special cases the dial is graduated point by point from a direct comparison with the mercury barometer, but this procedure is impracticable with commercial instruments of the usual pattern. The usual procedure with these is as follows: Having made the mechanism to work as well as possible, the relative amounts of steel and brass on the compensating lever are adjusted at atmospheric pressure, either until the indication of the hand does not change over the desired temperature range, or until the change is the correct amount to compensate the expected change on the scale value at any desired part of the range. In aneroids used mainly at atmospheric pressure the first rule is adopted, while for altimeters it is best to attempt to make the thermal error to be zero in the neighbourhood of the expected usual flying altitude.

If the corrections of the readings of a newly-assembled aneroid be plotted against the true pressure, the graph will in general not be linear. It will take some form as the curve *A*, Fig. 8. By suitably adjusting the mechanism it is usually possible to vary the velocity ratios of its different portions until the graph becomes reasonably straight, *B*, Fig. 8. To correct the error in the scale value shown by the slope of the correction curve *B*, the adjusting screw *L*, Fig. 1, is altered until the curve *C*, Fig. 8, represents the corrections.

Here again the temperature at which the instrument is likely to be used, the effect of temperature on scale value, and in the case of altimeters the particular relations assumed in the elevation scale adopted will determine the form of the final calibration curve in terms of the mercury barometer, which is always employed as the reference standard.

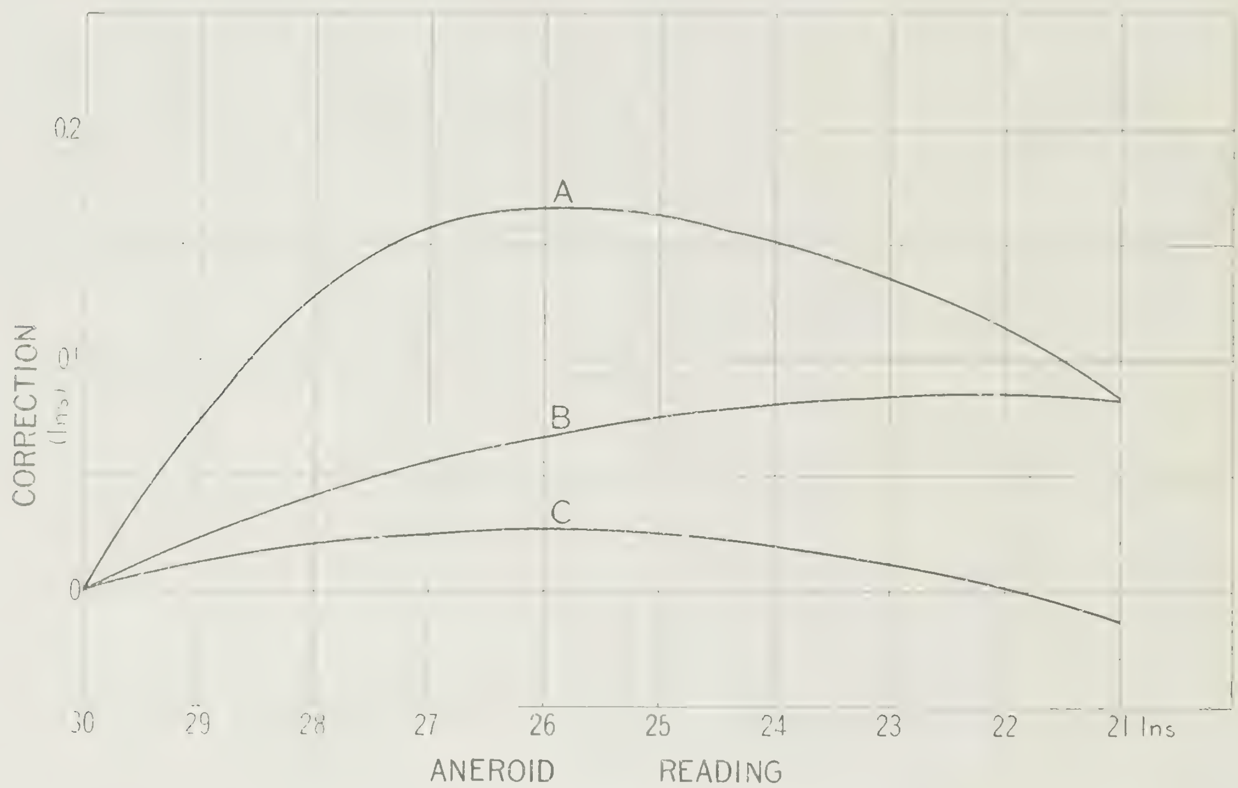

Fig. 8

GRAPHS ILLUSTRATING THE SHOP ADJUSTMENT OF AN ANEROID BAROMETER

A. Calibration curve of uncorrected instrument.
B. Calibration curve after angular velocity ratios have been adjusted to give regular corrections.
C. Calibration curve after magnification ratio has been adjusted to give scale value approximately equal to unity. A test like that giving rise to the curves in Fig. 3, and a knowledge of the usual temperature of operation enables the scale value to be adjusted to give minimum calibration errors at this temperature.

The Testing of Aneroid Barometers.—At the Physical Testing Laboratory, where several hundreds of aneroids and altimeters are tested annually, means are provided for making the various tests and adjustments to determine or correct the errors already descibed.

The apparatus consists of mercury barometers of the Kew or cistern type to serve as standards of comparison with a Fuess standard mercury barometer as a reference standard.

During most of the test the aneroids are placed in cast iron containers covered by heavy plate glass. A motor-driven air pump exhausts the containers as desired, the pressure within the container being indicated by one of the barometers.

For the thermal tests the containers are placed in a windowed chamber which is provided with coils through which hot or cold water can be circulated. Some of the containers are also water jacketed so that the desired temperature can be more quickly reached and held at the desired points.

Part of the apparatus of the Physical Testing Laboratory is illustrated in Fig. 9. The thermal chamber is seen to the left, and at the right is one of the cistern barometers. Two containers are on the bench.

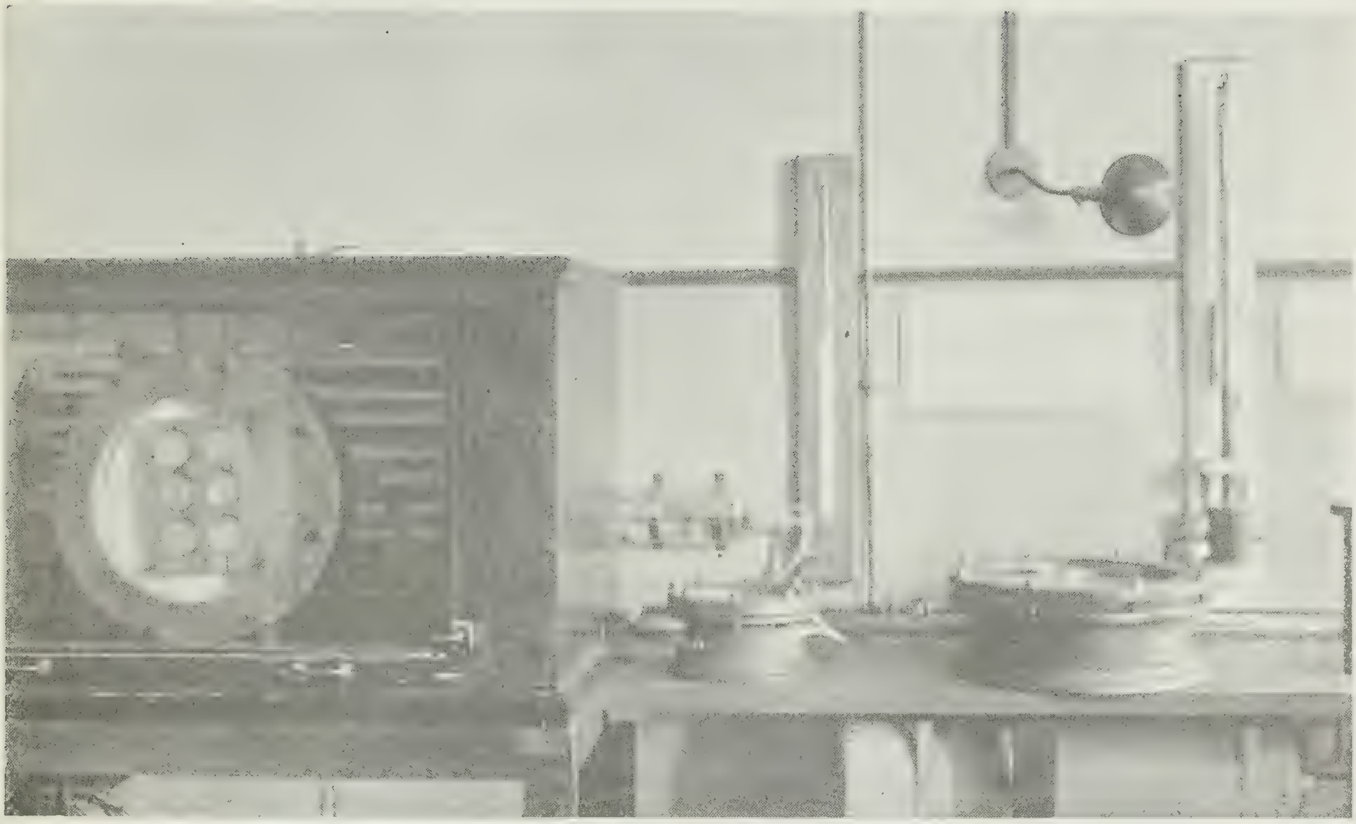

FIG. 9

ANEROID TESTING APPARATUS

To the left is seen the thermal chamber, with a container holding six aneroids under test. Two more containers are on the bench. For resisting the pressure differences encountered in calibrating high range altimeters, one-inch thick plate glass has to be used for covering the containers. A cistern barometer is seen near the right. For very low temperature tests a special refrigerator chamber is employed.

A special refrigerator chamber is used by the Laboratory for testing altimeters and special instruments at temperatures as low as $-40°C$, as illustrated in Figure 10.

The "Tapping" and "Shift" errors are readily found by an experienced operator without the aid of special apparatus. A comparison with the mercury barometer at the standard rate of one inch of mercury per five minutes, or one thousand feet in five minutes for altimeters, gives the calibration errors. The instrument is allowed to stand for five hours at a pressure corresponding to the lower end of its scale, after which the pressure is allowed to increase at the standard rate, while the calibration corrections are again determined. The interval between the two sets of calibration corrections is a measure of the drift in five hours. It is usual to take the mean of the differences at each inch (or one thousand feet in the case of altimeters) and divide by the total pressure (or height) difference from atmospheric, expressing the result as a percentage.

The constant-pressure thermal effect is found by subjecting the aneroid to at least three temperatures over the desired range and comparing it with the mercury barometer at each temperature, while the scale-value thermal error is obtained by carrying out calibration tests at the requisite temperatures. In all thermal tests the instruments are allowed sufficient time to come to a steady temperature before readings are taken.

Type altimeters may also be subjected to a vibration test to determine the accumulation of errors under vibration such as may occur in use.

Barographs and aneroids of special design are tested by slight modifications to this program or by simple adaptations of the apparatus.

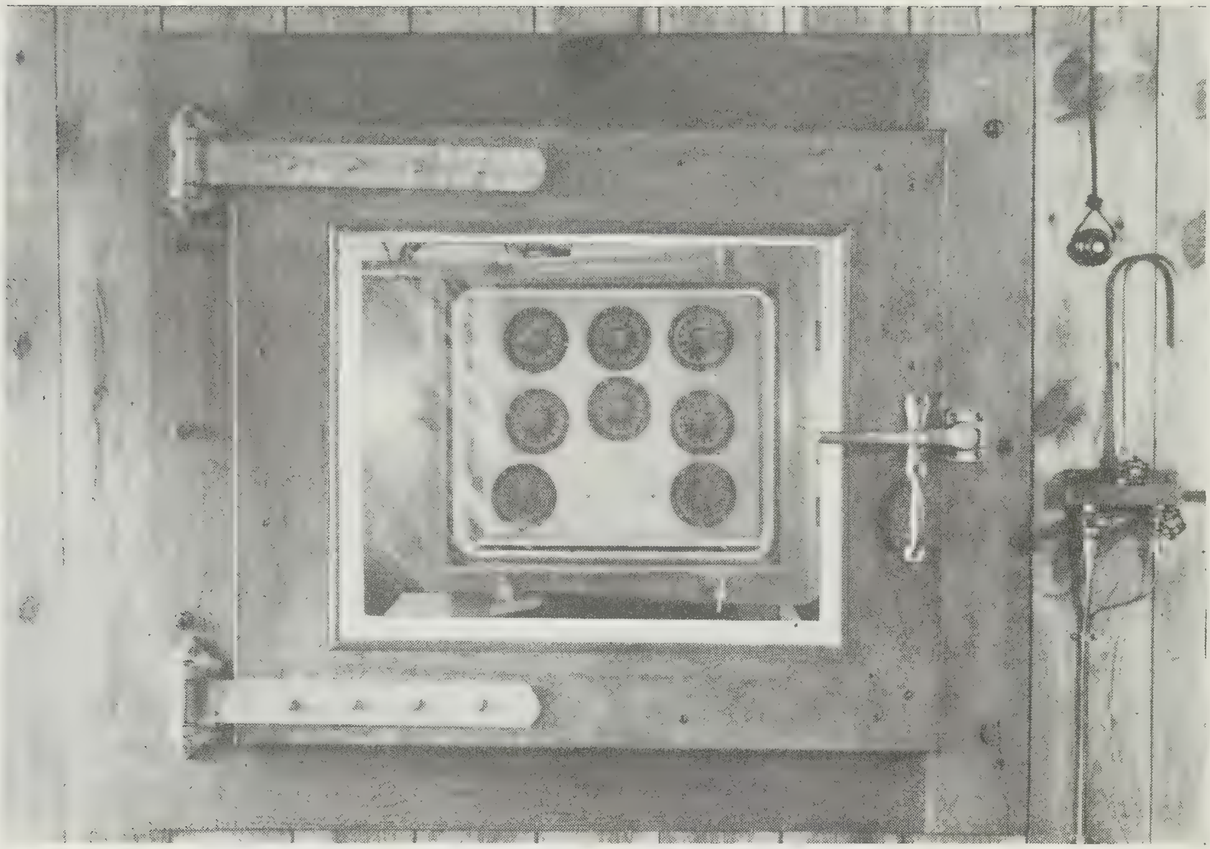

FIG. 10

REFRIGERATOR CHAMBER

Special refrigerator at the Physical Testing Laboratory for testing aneroid barometers and other instruments at low temperatures. It consists of a well insulated chamber cooled by the direct expansion of carbon dioxide. Some altimeters are seen under test, in the inner air-tight container in which any desired pressure can be maintained.

THE USE OF ATMOSPHERIC PRESSURE IN DETERMINING ELEVATIONS

The air being a fluid, use can be made of the pressure differences between different levels to measure the elevation changes between these levels. However, owing to the various effects we call weather, the atmosphere is never in a static condition and while some of the variable quantities can be allowed for, others must be neglected or an average value assumed for them. In general the data from which elevations are computed are the barometric pressures at the upper and lower levels and the temperature at one or more points at or between these levels. It is stated[1] that actual altitudes can be computed to an accuracy of from 0·5 to 2 per cent by means of the barometric formulæ.

Standard Formulæ.—For graduating the dials of altimeters some formula has to be assumed for the relation between pressure and height under standard conditions. Obviously the standard conditions will be more or less different from the actual ones, and the best that can be done is to make the standard as near as possible to the average, and for precise observations apply corrections. In general the largest correction to be applied to the height indicated by an altimeter is that due to the effect of temperature on the density of the air. Humidity has a small effect, but most other factors may be disregarded.

[1]Brombacher "The Determination of the Altitude of Aircraft", Journal of the Optical Society of America, Vol. 7, No. 9.

Isothermal Atmosphere.—Until recently it was the universal practice to calibrate altimeters to what is known as the Isothermal Atmosphere. In this relationship it is assumed that the temperature is the same at all heights. The formula for the isothermal atmosphere is:—

$$h = 62580 \log_{10} \frac{P_o}{P} \qquad (1)$$

where h = the height in feet.

P_o = the barometer pressure at the lower level.

P = the barometer pressure at the upper level.

The air is at a temperature of 10° C. (50° F.).

Where the mean air temperature is different from 10°C., a correction has to be applied to the formula (1). The correction, C, is:—

$$C = h \frac{t - 10}{283} \qquad (2)$$

where t is the mean temperature of the air between the two stations where the pressures are P_o and P respectively, and it is assumed that the air behaves as a perfect gas. The correction (2) amounts to about 3·5 feet per one thousand feet computed height for each degree centigrade that the mean temperature differs from 10°C. or 2·0 feet per one thousand feet if the Fahrenheit thermometer is used, differences in this case being taken from 50°F. When the mean temperature is lower than 10°C. or 50°F. the correction has to be subtracted from the observed height and for a higher mean temperature the correction must be added.

The Bureau of Standards, Washington, employs a slightly modified form of (1) in which account is taken of an average degree of humidity. Inasmuch as the air is never perfectly dry, heights computed from (1) will always be slightly less than if humidity had been taken into consideration. The Bureau of Standards isothermal atmosphere equation is:

$$H = 62900 \log_{10} \frac{P_o}{P} \qquad (3)$$

and is the relation employed for graduating the height scales on surveying aneroids used by the Topographical Survey of Canada, where P_o is taken as 29·90 inches of mercury.

Standard Atmosphere.—Up to heights of a few thousand feet the isothermal atmosphere represents fairly average conditions, but for the greater elevations now being attained by aircraft it is based on temperatures that do not apply. It is advantageous to graduate altimeter dials so that they will indicate approximate heights under average conditions likely to be encountered. and for this purpose an isothermal atmosphere is not suitable. For this and other reasons an International Standard Atmosphere has been adopted. In the Standard Atmosphere it is assumed that the air at sea level is at a temperature of 15°C., and that the air temperature varies uniformly with the height, up to a height of 11,000 metres, according to the relation:[1]

$$\vartheta_z = 15 - 0 \cdot 0065Z \qquad (4)$$

where

ϑ_z is the air temperature at the height Z, units being centrigrade degrees and metres.

This lapse rate of temperature corresponds to about 2·0°C or 3·6° F per one thousand feet rise in elevation.

[1]Air Publication No. 1173, British Air Ministry.

The formula for height up to 11,000 metres, according to the standard atmosphere , is:

$$\frac{p_z}{p_o} = \left(\frac{288 - 0 \cdot 0065Z}{288}\right)^{5 \cdot 256} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where

p_z = The barometric pressure at the height Z.
p_o = The barometric pressure at the height zero.

Table I, below, shows the heights indicated by altimeters graduated according to the equations (3) (isothermal) and (5) (standard) when subjected to the barometric pressures given. In both cases zero height has been taken as equivalent to a pressure of 29·92 inches (1013·2 millibars). Older tables are usually based on a pressure at sea level of 29·90 inches of mercury.

TABLE I

Comparison of relation between barometric pressure and height for the two standard laws assumed in calibrating altimeter dials.

Barometer Pressure Inches of Mercury	Height	
	Isothermal Law	Standard (I.C.A.N.) Law
30·6	− 610	− 620
29·92	0	0
29·0	+ 850	+ 860
28·0	1,800	1,820
26·0	3,820	3,830
24·0	5,990	5,970
22·0	8,360	8,260
20·0	10,950	10,730
18·0	13,810	13,400
16·0	17,010	16,320
14·0	20,640	19,560
12·0	24,830	23,200

Computation of Elevations from Barometer or Altimeter Indications.—In cases where the elevation is desired with more than approximate precision, temperature corrections must be applied to the heights indicated by an altimeter or computed from barometric readings. For surveying purposes where the isothermal relation is generally employed it is usual to take the air temperature as the arithmetical mean of the temperatures at the upper and lower stations, and apply a correction of two feet per thousand feet of elevation difference for each degree Fahrenheit that the arithmetical mean temperature differs from 50°F.

In aeronautical work, while greater heights are involved, the temperature correction is still frequently employed in the same way when altimeters graduated according to the isothermal atmosphere are used. Another method is to read the temperature at the upper level by means of a strut thermometer and compute the mean temperature from the lapse rate (4) or from data more nearly applicable to local conditions, if such are available. For most purposes, it is sufficient to take the mean temperature of the layer of air considered as:

$$t + \tfrac{1}{2}\, a\, H \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where

t is the temperature indicated by the strut thermometer.
a is the assumed lapse rate of temperature with height.
H is the height indicated by the altimeter.

Table II is computed on these assumptions, employing a lapse rate of 2·0°C per 1,000 feet elevation. It shows the corrections to be employed, for various strut thermometer readings, to the heights indicated by altimeters correctly calibrated to the isothermal atmosphere.

TABLE II

Corrections to be applied to the indications of altimeters graduated to the isothermal height scale, to give the correct height for air temperature observed at the height of the altimeter.

ISOTHERMAL ATMOSPHERE (10°C)

Strut Thermometer Reading	Correction to be applied to altimeter indications of										
	2,000	4,000	6,000	8,000	10,000	12,000	14,000	16,000	18,000	20,000	25,000
	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.
+20°C...	+ *90*	+ *210*	+ *350*	+ *530*	+ *730*	+ *970*					
15.....	*50*	*130*	*240*	*380*	*550*	*750*	+ *980*				
10.....	+ *10*	+ *60*	*130*	*230*	*370*	*530*	*720*	+ *940*			
+ 5.....	− 20	− 10	+ *20*	+ *90*	+ *180*	*310*	*460*	*650*	+ *860*		
0.....	60	90	− 90	− 60	*0*	+ *90*	+ *210*	*350*	*530*	+ *730*	
− 5.....	100	160	200	210	− 180	− 130	− 50	+ *60*	+ *200*	+ *370*	
10.....	130	230	310	350	370	350	310	− 230	− 130	*0*	+ *460*
15.....	170	310	420	500	550	570	570	530	460	− 370	*0*
20.....	210	380	530	650	730	790	820	820	790	730	− 460
25.....	240	460	640	790	920	1,010	1,080	1,120	1,120	1,100	920
30.....	280	530	750	940	1,100	1,230	1,340	1,410	1,450	1,470	1,380
35.....	320	600	860	1,090	1,280	1,450	1,590	1,700	1,780	1,830	1,840
−40°C...	− 350	− 680	− 970	− 1,230	− 1,470	− 1,670	− 1,850	− 2,000	− 2,110	− 2,200	− 2,290

These corrections are based on a lapse rate for temperature of 2·0°C per 1,000 feet, and are computed from the formula, Correction $= 3.7\ H\ (H + t—10)$, and must be applied in addition to the corrections for any thermal errors the instrument may have.

The figures in italics must be added to the observed height. The plain figures, below the italics, must be subtracted from the observed height.

When altimeters calibrated to the standard atmosphere are employed the corrections may still be fairly easily computed if assumptions are made which are not likely to introduce any error which is large when compared with those due to the uncertainty in the applicability of the assumptions governing the instrument calibration to the particular conditions under which the observations are being made.

The standard mean temperature of the air layer between zero elevation and the height H (in thousands of feet) may be considered, without serious error, as 15—H in degrees centigrade for the relations assumed in the standard atmosphere. Similarly if a strut thermometer at the height H indicates a temperature t°C, the actual mean temperature of the air layer may be assumed to be t + H. Consequently a formula such as:—

$$\text{Temperature Correction} = 4(2H + t - 15)H \text{ .... } (7)$$

may be applied to the indications of an altimeter calibrated according to the standard atmosphere. Formula (7) is given by the British Air Ministry, and if the strut thermometer be read at some other height, h, different from H, the formula may still be applied in the form:—

$$\text{Correction} = 4(2h + t_h - 15)H \text{ .... } (8)$$

Table III gives some typical corrections computed from equation (7) for various altimeter and strut thermometer readings.

The subject has only been cursorily treated here and approximate correction formulæ considered. Where greater precision is aimed at the reader is referred to such publications as:—

British Air Ministry Air Publication No. 1275, Section 4, Chapter 1; The Journal of the American Optical Society, Vol. 7, No. 9, "The Determination of the Altitude of Aircraft" by W. G. Brombacher; The National Advisory Committee for Aeronautics, Washington, Reports Nos. 147, 218, and 246.

TABLE III

Corrections to be applied to the indications of altimeters graduated to the standard (I.C.A.N.) height scale to give the correct height for air temperatures observed at the height of the altimeter.

STANDARD (I.C.A.N.) ATMOSPHERE

Strut Thermometer Reading	Correction to be applied to altimeter indications of										
	2,000	4,000	6,000	8,000	10,000	12,000	14,000	16,000	18,000	20,000	25,000
	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.	ft.
+20°C...	+ *70*	+ *210*	+ *410*	+ *670*	+ *1,000*	+ *1,390*					
15.....	+ *30*	*130*	*290*	*510*	*800*	*1,150*	+ *1,570*				
10.....	− 10	+ *50*	*170*	*350*	*600*	*910*	*1,290*	+ *1,730*			
5.....	50	− 30	+ *50*	*190*	*400*	*670*	*1,010*	*1,410*	+ *1,870*		
0.....	90	110	− 70	+ *30*	+ *200*	*430*	*730*	*1,090*	*1,510*	+ *2,000*	
− 5.....	130	190	190	− 130	*0*	+ *190*	*450*	*770*	*1,150*	*1,600*	
10.....	170	270	310	290	− 200	− 50	+ *170*	*450*	*790*	*1,200*	+ *2,500*
15.....	210	350	430	350	400	290	− 110	+ *130*	*430*	*800*	*2,000*
20.....	250	430	550	610	600	530	390	− 190	+ *70*	+ *400*	*1,500*
25.....	290	510	670	770	800	770	670	510	− 290	*0*	*1,000*
30.....	330	590	790	930	1,000	1,010	950	830	650	− 400	+ *500*
35.....	370	670	910	1,090	1,200	1,250	1,230	1,150	1,010	800	*0*
−40°C...	− 410	− 750	− 1,030	− 1,250	− 1,400	− 1,490	− 1,510	− 1,470	− 1,370	− 1,200	− 500

These corrections are based on a lapse rate for temperature of 2·0°C per one thousand feet and are computed from the British Air Ministry approximate formula—Correction= $4H(2H + t - 15)$. They must be applied to the altimeter reading after this has been corrected for any thermal errors the instrument may have.

The figures in italics must be added to the observed height. The plain figures, below the italics, must be subtracted from the observed height.

Users of aneroid barometers and altimeters should remember that there are two distinct temperature corrections with which they are concerned. First there is the effect of temperature on the indications of the instrument. This effect is entirely independent of the atmosphere in so far as, while the atmospheric pressure remains constant, the instrument indication may change if the instrument temperature is altered, say by local heating.

Secondly, there is the effect of temperature on the density of the air. If the atmospheric temperature increases the air becomes lighter and hence the pressure difference decreases between two levels. This effect is entirely external to the instrument, and in no sense depends on its characteristics.

This distinction is emphasized as some persons are apt to think that the word "compensated" on an aneroid dial means that the instrument will measure elevation differences correctly at all atmospheric temperatures, and moreover, many users find it difficult to understand why two entirely different temperature corrections are associated with the use of the aneroid barometer. Two temperature corrections would need to be applied had a mercurial barometer been used instead of the aneroid type, the first to allow for the expansion of the mercury and scale, and the second for the density of the air.

One source of error in the reading of altimeters first pointed out by Mr. R. D. Davidson, D.L.S., is a venturi effect due to the motion of the aeroplane. In general this will cause too great an elevation to be indicated. It can be practically eliminated by sealing the case of the altimeter and connecting it by

tubing to a special head, located on the frame of the plane, that will be subject to the true static atmospheric pressure. Experiments have shown that for the effect to be entirely eliminated the static pressure head must be located thirty feet or so away from the plane. One well known American firm manufactures its altimeters with sealed cases having threaded connections so that static heads can be used to communicate the static air pressure to the instruments. The venturi error may amount to one hundred feet or more.

Barometric fluctuations at a given level affect the pressures at other levels and must be allowed for. In the case of altimeters used for long distance flights an auxiliary scale graduated in inches of mercury pressure is sometimes fitted, this scale being fixed and the usual height scale made rotatable. When a pilot approaches a station where he wishes to land in fog or by dark the barometer reading at the station is telegraphed to him and he sets the zero of his rotatable scale opposite the pressure given. Provided the altimeter is properly adjusted, he will then know that he can rely upon the height indicated at any moment being the true height above the ground where he is desiring to land.

STANDARD SPECIFICATIONS FOR SURVEYING ANEROID BAROMETERS

Below are given the standard specifications for surveying aneroid barometers, prepared by the Physical Testing Laboratory:—

GENERAL

The case shall be rigid, preferably of brass, but not of aluminium and approximately 3 inches outside diameter. The dial shall be accurately graduated with two scales fixed relative to each other, the inner scale showing inches of pressure and the outer, feet altitude. These scales shall be subdivided to 0·01 inch and 10 foot intervals for instruments having ranges up to 4,000 feet; 0·02 inch and 20 feet for ranges above 4,000 feet and up to 8,000 feet; and 0·05 inch and 50 feet for ranges above 8,000 feet. The relation between the two scales shall be according to the equation:—

$$H = 62900 \log_{10} \frac{29 \cdot 90}{P} + 1{,}000$$

Where H is the indicated height in feet on the elevation scale and P is the corresponding pressure in inches of mercury, on the pressure scale.

The scale shall be equiangular for equal increases in altitude. The graduation marks shall be sharp, regular, and distinct with minimum width consistent with good visibility. The hand shall be mounted as close to the dial as possible without danger of interference and the breadth at the end over the graduations shall be a minimum.

MECHANISM

The aneroid shall be compensated for temperature so that the error from this source shall be a minimum at the midpoint of the scale in addition to being within the tolerance given under criterion (6) below. The mechanism shall be designed and constructed with due regard for the obtaining of accurate results in surveying operations. In particular the carriage supporting the main-spring shall be held rigidly, and in such a way that looseness will not develop under ordinary treatment in service. (The usual design, with the carriage supported on three screws, has not been found satisfactory in this respect.) The method employed for setting the hand shall be such that it cannot be disturbed by jars given to the instrument. The main-spring shall be held rigidly in the carriage, preferably with screws passing through the spring, and the knife-edge shall be carefully located on the spring so that no relative movement will take place in service and alter the indications of the hand from this cause. All hinge joints and pivots shall be carefully fitted and properly finished to diminish friction, but avoid backlash. The workmanship generally must be first-class.

The contractor shall submit for approval with his tender a sample aneroid or a drawing or photograph showing the design of mechanism in the aneroids it is proposed to supply.

TEST

The instrument, before acceptance, will be subjected to the following test at the Physical Testing Laboratory, and its performance must comply with the tolerances given below:—

Program of Test

Part	Name of test	Remarks
1.	Preliminary examination..	Instrument examined for mechanical and other defects.
2.	Temperature test at normal pressure..	Instrument maintained at constant pressure while temperature is varied.
3.	Calibration and Drift..	Instrument calibrated at 20° C and drift in five hours determined.
4.	Temperature test with diminishing pressure..	Instrument calibrated at 0° C and 40° C.

Part 1.—The instrument is given a general examination to check the design, workmanship and existence of any obvious defects, or failure to comply with the requirements set out above. It is then subjected to the following tests to detect friction, looseness, lack of rigidity and want of balance:—

1. The instrument is tapped and the maximum range within which the hand comes to rest is recorded as the deviation by tapping.

2. The instrument is held in the horizontal position and struck with some force against the palms of the observer's hands, first against the one hand and then (without rotating it) against the other. In each case a reading is taken immediately afterwards in the horizontal position. During several repetitions of this test, the greatest difference between any two (not necessarily consecutive) readings is recorded as the shift.

3. The instrument is read in the horizontal position, after tapping gently, and immediately afterwards in the vertical position. The variation in reading gives the vertical correction.

Part 2.—The aneroid is placed in the thermal chamber and allowed to remain at a constant temperature of 20° C for at least three hours. A comparison is then made between the readings of the aneroid and the true pressure, as given by the mercury barometer. The temperature of the chamber is then reduced and held at 0° C for a further three hours. The reading is again recorded and compared with that of the standard barometer. After the chamber has been heated to 40° C the aneroid is allowed to remain at this temperature for four hours, and another comparison made with the standard. A final comparison is made after the aneroid has stood at the original temperature, 20° C, for a period of three hours. Throughout this part the aneroid remains at a pressure approximately equal to normal pressure (30 inches).

Part 3.—The calibration errors at normal temperature (20° C) are determined while the pressure is being reduced at the rate of one inch of mercury in five minutes, readings being taken at every inch of the scale. When the index has reached the lowest pressure intended to be read, the pressure is maintained constant for five hours. A second set of readings is then taken while the pressure is allowed to increase at the rate of one inch in five minutes. The drift is determined by the change in the corrections during the five hour interval.

Part 4.—The temperature test is divided into two portions, the instrument being calibrated in the thermal chamber at temperatures of 0°C and 40°C. Before calibration the instrument is allowed to stand at the temperature of test for three hours, the pressure being then reduced at the normal rate of one inch in five minutes. Comparisons are made between the aneroid and the mercury barometer at every inch. The results of the decreasing pressure test, Part 3, giving the calibration corrections at normal temperature, are taken in conjunction with this test.

TOLERANCES

The tolerances allowed in the above tests are as follows:—

(1) The deviation by tapping shall not exceed 0·01 inch of mercury.

(2) The shift shall not exceed 0.01 inch of mercury.

(3) The vertical correction shall not exceed 0.04 inch of mercury.

(4) The proportional drift shall not exceed 0.005 inch of mercury.

(5) When the calibration corrections at any temperature are plotted to scale, the average deviation of the points from the mean straight line drawn through them shall not exceed 0.02 inch of mercury, and the greatest deviation at any point from this line shall not exceed 0.04 inch of mercury. If the points lying above the mean straight line be taken as having positive deviation and points below the line negative deviation, the algebraic difference between the deviations of any two consecutive points one inch apart shall not exceed 0.03 inch of mercury.

(6) (*a*) The greatest variation in reading at normal pressure in the range 0°C to 40°C shall not exceed 0.08 inch of mercury.

(*b*) The greatest variation in reading at normal pressure in the range 0°C to 20°C or 20°C to 40°C shall not exceed 0.05 inch of mercury.

(7) The greatest difference in scale value between 0°C and 40°C shall not exceed 2 per cent.

DEFINITION OF TERMS USED ABOVE

"Drift" is the amount of decrease in reading when an aneroid remains at a constant but reduced pressure.

In the above test the "Proportional Drift" is obtained as follows:—

In the calibration tests (part 3) readings are taken at each of the points, 30 inches, 29 inches, 28 inches, etc., to the smallest reading of the instrument. The mean of the differences between the calibration corrections at each of these points, with the pressure increasing and decreasing respectively, is computed. This mean, divided by the total drop in pressure from 30 inches to the lowest reading, (which is held for five hours) is the proportional drift.

"Scale value" is the mean value of one unit on the scale of the aneroid in terms of the true pressure change.

APPENDIX

THE FIELD USE OF THE ANEROID BAROMETER

By G. C. Cowper, D.L.S.

The Topographical Survey, Department of the Interior, has successfully used aneroid barometers since 1919 for contouring the sectional map sheets in Western Canada (scale three miles to one inch) to an interval of fifty feet.

The following description of the field methods which have been standardized by the Survey, shows that the barometer when properly used and controlled by levels, gives very rapid and surprisingly accurate results.

Before the topographer can intelligently use the barometer in the field, he should have a thorough knowledge of the errors which may affect the indicated elevations. These errors are described in detail in the first part of this bulletin; the following are those which are of the most importance to the topographer:

I. Mechanical Errors

(*a*) Lack of balance of moving parts. To avoid this error, the instrument must always be read in one position. The standard position for surveying is with the dial horizontal.

(*b*) Frictional error. To avoid excessive frictional error, tap the glass gently before reading the instrument.

(*c*) Looseness of moving parts. Sudden jumps in the reading of an aneroid may be caused by heavy jars given to the instrument between observations. The aneroid should be safeguarded against falls or other rough treatment.

(*d*) Elastic lag or drift. The reading of an aneroid will continue to alter in the direction of the pressure change after the pressure has become steady. Any considerable heights should be ascended and readings taken as quickly as possible.

II. Calibration Errors

All aneroids used by the Topographical Survey have been adjusted at the Physical Testing Laboratory so as to have minimum calibration errors at room temperature. With moderate changes of elevation and short periods between readings on known elevations, these errors will be compensated out in the adjustments usually made.

III. Thermal Errors

Most aneroids are marked "Compensated" and the impression is given that their readings are not affected by temperature changes. This is only true, as a rule, at one pressure. As pointed out in the discussion on temperature errors in the first part of this bulletin, it is not possible to adjust the compensation to be correct at more than one part of the scale. Aneroids should be protected from sudden changes in temperature and should be exposed for at least 20 minutes to the temperature at which they are to be used before any readings are taken. They should not be exposed to direct sunlight long enough to heat up the exposed portion of the case. The error due to change in temperature, as in the case of the drift and calibration errors, may be neglected where only short intervals of time elapse between readings on known elevations.

Contouring Small Scale Maps.—In the field the barometers are carried in sets of three in a specially made box which has a mean time watch fitted in the cover, the field watches being synchronized with the camp watch. The three instruments are read at each point for which an elevation is required, the time of each reading being also noted. It is hoped that with the improved instruments now being obtained, in the future only one barometer will be required. The barometers are read to the nearest five feet and for convenience in working out the final corrections an even thousand feet is subtracted from the readings before they are recorded. This is done because the zero on the foot scale is placed approximately opposite the 31-inch mark on the pressure scale, and consequently the readings on the foot scale are 1,000 feet too high. In reading the barometers, care is taken to look directly down on the instrument so that there will be no parallax, the glass is gently tapped to overcome friction, and the relation between the three barometers should remain fairly constant. One barometer may go up twenty feet, while the other two only go up ten, but this difference should not be exceeded. This relation can usually be kept fairly constant by repeated tapping.

During the field day, three barometers are read in camp every half hour, from which observations the curve or gradient showing the changes in atmospheric pressure is plotted. The camp barometers are kept as far as possible under the same conditions as the field instruments; that is, they are kept out of doors and shaded from the sun.

In commencing a barometric survey the instruments are first read at a known elevation and the last reading of any circuit must also be at a known elevation. The accuracy of the work is largely dependent on the interval of time between these two readings, and for this reason an adequate instrumental level control is necessary. On the sectional sheet surveys, these lines are run from two to six miles apart. It has been found that the best results are obtained when the time interval between known elevations does not exceed thirty to forty minutes and only when unavoidable should more than one hour elapse between these readings. In settled country where the roads are opened up and one can travel by motor car, it is not difficult to keep the time interval well within an hour, but in unsettled districts where the work must be done on foot, a longer time must be tolerated with a corresponding loss of accuracy.

When motor cars are used the barometers are read at a known elevation and carried as quickly as possible along a road to the next known point, readings being taken and the topography sketched at all intervening section and quarter-section corners, as well as at the more prominent summits and depressions. By arranging the work so that the interval between readings on known elevations does not exceed thirty minutes, the elevations of the points noted can be determined directly from the readings and the contours sketched on the township plans, using a hand level for tracing their courses across the interval between the roads. In this case the camp gradient is only used in checking the accuracy of the elevations as determined in the field, as it has been found that when the interval between readings on known elevations does not exceed thirty minutes, no corrections are necessary to the elevations used in the field. When the time interval exceeds thirty minutes it is usually necessary to use form line sketching and complete the contouring in the camp office, or else contour in the field after the barometric readings have been reduced with the aid of the camp gradient.

Where walking has to be resorted to, the barometers are read as often as possible on known elevations, and when the time interval exceeds two hours the work is so arranged that readings can be taken at some points on two or more different circuits. These points are called repeat stations, and in the final corrections to the readings the mean of the elevations of the repeat stations are used as known elevations. The contours are then drawn in the office with the aid of form line sketching.

If it can be avoided, barometric levels should not be carried over deep valleys or other large and sudden changes in elevations where the readings may be seriously affected by lag, or causes external to the instrument such as wind, air strata, temperature variation, etc. It is usual to complete the work on one side of an obstacle and then to cross over and give the aneroids time to recover before proceeding with the survey. For this reason the camp should not be placed in valleys.

On the prairie sections of Western Canada where the atmospheric conditions are usually fairly constant over large areas, work may be carried on as far as twenty miles from camp. This distance should be materially reduced in a broken or mountainous country where the air currents are more or less affected by the broken surface of the country.

In cases where a thunderstorm or other violent disturbance is encountered, it is neceessary to return to the last known elevation at which a reading was taken and start the survey again after the disturbance has passed. There are, however, days when barometer work is impossible, as no camp readings or frequency of ties will keep up with the variations in pressure, when readings on the same spot may vary 40 or 50 feet in a few minutes. Fortunately such days are rare, but when any such condition is detected it is useless to carry on with barometer work.

Reduction of Readings.—Aneroid readings may be corrected for the daily changes in atmospheric pressure, for temperature calibration, lag etc., but if all these corrections are made the reduction of the readings becomes so laborious that the advantages of the aneroid in speed and economy would be lost. The practice adopted is to correct only for atmospheric pressure, and to lump all the other corrections, which are usually small, in what is called the correction to datum.

In reducing the readings the first procedure is to plot the camp readings on profile paper and draw in the gradient curve showing the changes in atmospheric pressure by joining these points.

Fig. 11 shows one day's readings of the camp barometers for the purpose of obtaining this gradient. In this case the three barometers were read every half hour, the readings being entered in their proper places. The means are then worked out and plotted. The line joining these plotted positions is the camp gradient curve. In the example the first readings were taken at 7.30 a.m. The mean of the three readings equals 1985, which furnishes the initial point of the curve in its plotted position. It can readily be seen that the other readings furnish other points for the curve. It is usual to assume as a base in determining the camp gradient corrections and in order to keep the latter always positive, an elevation greater than any touched by the curve during the day. In the example 2018 is the highest mean, and any elevation above this would be suitable for a base. The elevation adopted is 2050. The camp gradient correction for any time during the day is the number of feet between the curve and the base, and may be scaled from the plot. The camp gradient correction is the first correction to be applied to the field readings, and serves to eliminate from them the fluctuations due to the changes in atmospheric pressure.

Fig. 12 is a diagrammatic representation of the township investigated, and Fig. 13 a sheet of field readings taken in this township on the same day that the camp gradient curve in Fig. 11 was obtained.

In Fig. 12 the level control along the north and south boundaries, and along the Canadian National railway, is shown. The route travelled in obtaining the barometric readings is indicated.

Fig. 13 shows the form of taking the barometric readings in the field. In this case three barometers are used, and the means obtained. The addition of the gradient correction, as obtained from the curve of Fig. 11, gives the cor-

Place - Wilkie Camp *Date* Sept. 25 1928 *Observer* L.V.P.

	ANEROIDS			Mean
	T.S.1370	T.S.1371	T.S.1372	
7				
	1995	2010	1950	1985
8	1965	1995	1935	1965
	1950	1985	1925	1953
9	1950	1995	1935	1960
	1955	1995	1935	1962
10	1955	1995	1935	1962
	1955	1995	1935	1962
11	1955	1995	1935	1962
	1965	2005	1940	1970
12	1975	2015	1950	1980
	1975	2020	1955	1983
1	1990	2025	1960	1992
	1995	2030	1970	1998
2	1995	2035	1970	2000
	1995	2035	1970	2000
3	2005	2040	1975	2007
	2010	2040	1980	2010
4	2010	2040	1980	2010
	2010	2045	1980	2012
5	2010	2050	1985	2015
	2015	2050	1990	2018
6	2010	2050	1985	2015
7				

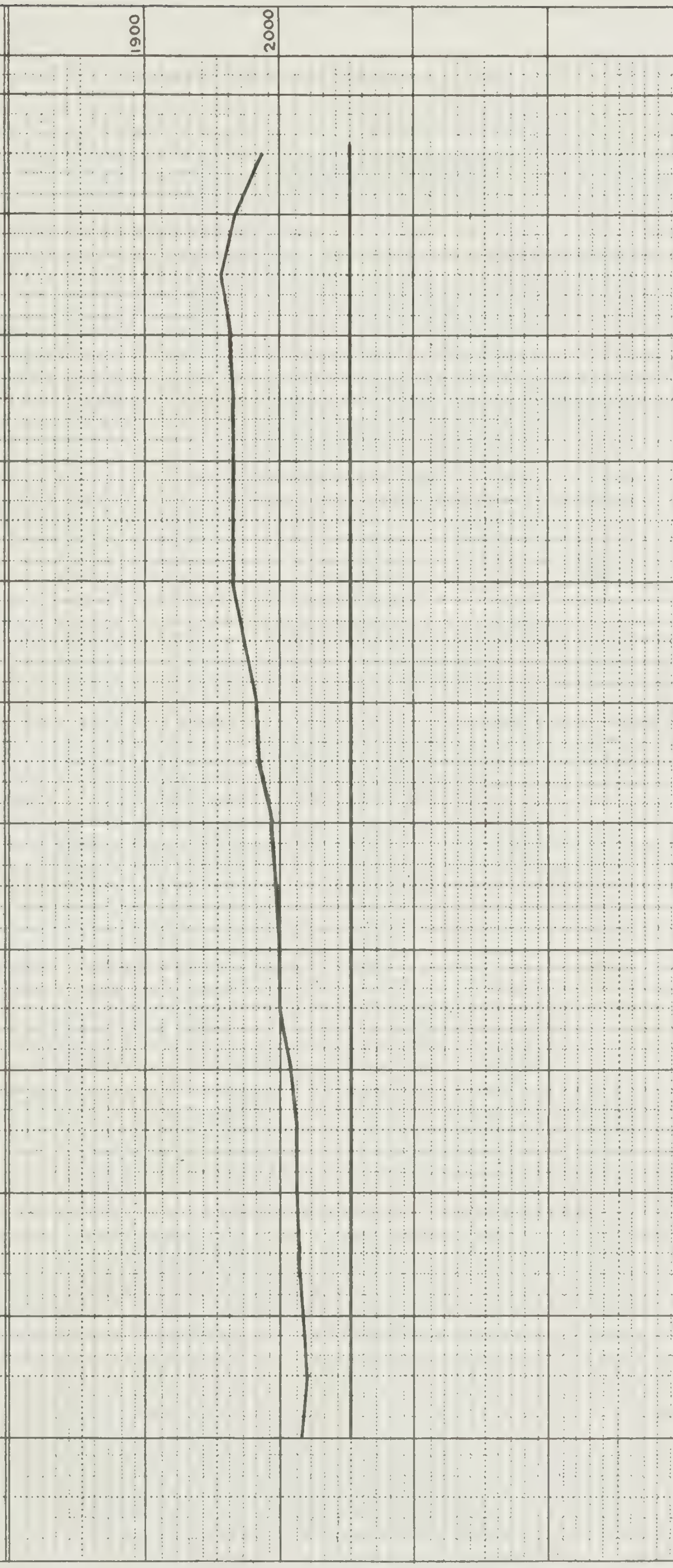

Fig. 11

A RECORD OF ONE DAY'S READINGS OF THE CAMP BAROMETERS

In this case three barometers were used and were read at half-hour intervals during the day. In the actual forms used in field practice the paper is cross-section ruled as an aid in placing the readings in their proper places and in plotting the camp gradient curve.

Form 156-4-29

Township 39 **Range** 20 **West of** 3rd. **Meridian**

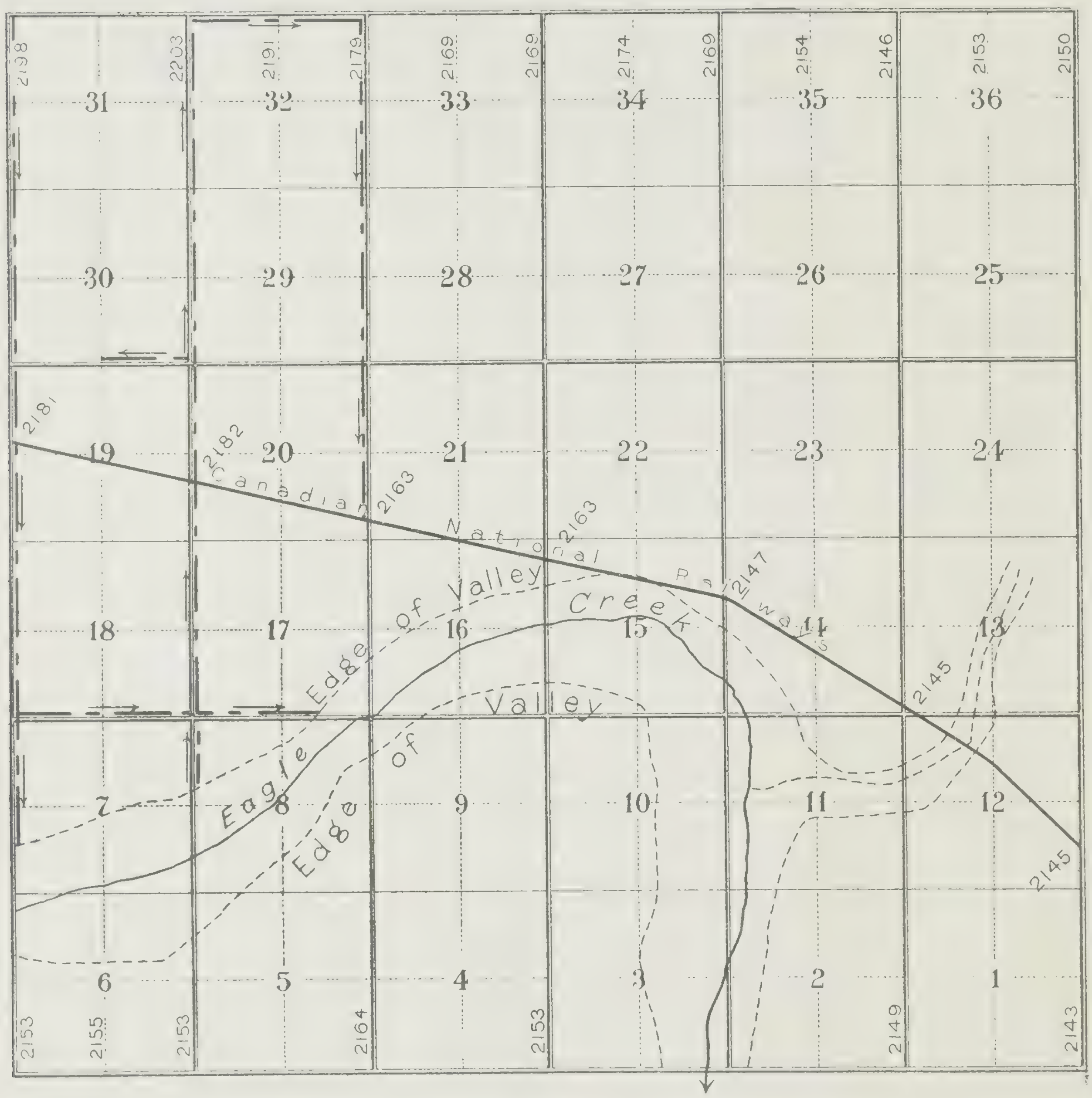

FIG. 12

DIAGRAMMATIC REPRESENTATION OF A TOWNSHIP OVER WHICH ANEROID READINGS WERE TAKEN

The route travelled along some of the township road allowances during one day is indicated. It commences at the northwest corner of the township and ends at the intersection of the east boundary of section 20 with the Canadian National railway. Along this route the elevations at the section line intersections with the Canadian National railway are accepted as final and the elevations indicated along the north boundary of the township are known. They furnish the control in obtaining the barometric elevations for the other points.

T.S. Form 322-5-29

Tp. 39 *R.* 20 *W. of* 3rd. *Mer.*

Date September 25. 1928 *Observer* G.C.C.

Reference	STATION Section	Tp.	R.	Course	Time	ANEROIDS T.S 101	T.S. 102	T.S. 103	Total	Mean	Gradient Corrn.	Corrd. Mean	REPEAT STATION Prelim. Corrn.	Prelim. Elevn.	Final Corrn.	Corrd. Elevn.	Reference	REMARKS
a	N.E. 36	39	21	S	8-40	1970	1945	1910		1942	95	2037	+161	2198	+161	2198	*a*	Known
b	¼ E 36	39	21	S	43	1970	1945	1910		1942	94	2036			161	2197	*b*	
c	N.E. 25	39	21	S	45	1960	1935	1900		1932	94	2026			162	2188	*c*	
d	¼ E 25	39	21	S	47	1950	1925	1890		1922	93	2015			162	2177	*d*	
e	N.E. 24	39	21	S	49	1960	1935	1900		1932	92	2024			162	2186	*e*	
f	E 24	39	21	S	51	1955	1930	1895		1927	92	2019	+162	2181	+162	2181	*f*	C.N.R.
g	N.E. 13	39	21	S	53	1960	1935	1900		1932	91	2023			162	2185	*g*	
h	N.E. 12	39	21	S	58	1955	1930	1895		1927	90	2017			162	2179	*h*	
i	E 12	39	21	S	9-05	1940	1915	1880		1912	90	2002			161	2163	*i*	Top of Valley
j	N.E. 7	39	20	E	28	1945	1920	1885		1917	88	2005			159	2164	*j*	
k	E 7	39	20	S	33	1920	1895	1860		1892	88	1980			159	2139	*k*	Top of Valley
l	¼ N 8	39	20	E	38	1925	1900	1865		1897	88	1985			159	2144	*l*	
m	N 8	39	20	E	40	1910	1885	1850		1882	88	1970			158	2128	*m*	Top of Valley
n	¼ E 18	39	20	N	48	1945	1920	1885		1917	88	2005			158	2163	*n*	
o	N.E. 18	39	20	N	50	1965	1940	1905		1937	88	2025			158	2183	*o*	
p	E 19	39	20	N	52	1965	1940	1905		1937	88	2025	+157	2182	+157	2182	*p*	C.N.R.
q	N E 19	39	20	N	54	1975	1950	1915		1947	88	2035			157	2192	*q*	
r	¼ N 19	39	20	W	58	1980	1955	1920		1952	88	2040			156	2196	*r*	
s	¼ E 30	39	20	N	10-00	1980	1955	1920		1952	88	2040			155	2195	*s*	
t	N.E. 30	39	20	N	02	1990	1965	1930		1962	88	2050			155	2205	*t*	
u	¼ E 31	39	20	N	04	1995	1970	1935		1967	88	2055			154	2209	*u*	
v	N.E. 31	39	20	N	06	1990	1965	1930		1962	88	2050	+153	2203	+153	2203	*v*	Known
w	N.E. 29	39	20	S	11	1960	1935	1900		1932	88	2020			153	2173	*w*	
x	N.E. 20	39	20	S	15	1955	1930	1895		1927	88	2015			153	2168	*x*	
y	E 20	39	20	S	18	1950	1925	1890		1922	88	2010	+153	2163	+153	2163	*y*	C.N.R.
z																	*z*	

FIG. 13

FORM OF RECORDING ANEROID BAROMETER READINGS IN THE FIELD

The readings from the three field barometers obtained in travelling over the route shown in Fig. 12 are given on the above form.

rected mean, which must receive its final correction to conform with the points of known elevations. The elevation of the northeast corner of section 36, township 39-21-3, as obtained from spirit levels, is 2198. The corrected mean for this station is 2037, consequently 161 must be added to the corrected mean to give the true elevation. The final corrections for all the known elevations are obtained in the same manner. The final corrections for the intermediate stations are obtained by interpolation between known elevations and the final elevations by adding or subtracting these values to the corrected means of the stations.

As the interval between readings on known elevations in the specimen of field notes does not exceed one hour, no repeat stations were used. When repeat stations are used the preliminary corrections to datum are obtained for each of the several readings at a repeat station by interpolation between known elevations and the resulting preliminary elevations are adjusted to a common value, either by taking the mean of the several elevations or by using a weighted mean which takes into consideration time intervals or weather conditions which may have affected some of these values. This adjusted elevation is entered in the column headed "Corrected Elevation" and is used as a known elevation in calculating the elevations of the intermediate stations.

The accuracy of barometric levelling is hard to determine exactly, but surprisingly accurate results have been obtained by the Topographical Survey during the past ten years. Using good barometers, taking care in reading them, and by having the interval between readings on known elevations to be less than one hour, it has been found that approximately 75 per cent of the barometric elevations are within five feet of the true elevations, and that very rarely is one found to be more than ten feet in error. When the barometers are carried by hand and repeat stations used, no reading should be twenty feet in error, while most of the elevations will be within ten feet. It must be remembered that these results can only be obtained on days suitable for barometric levelling.

In all barometric work allowance must be made for the fact that the aneroid only measures the weight of the air above the station at which the elevation is required. The atmospheric conditions are constantly changing and are affected by many obscure agencies for which it is impossible to obtain accurate corrections. Consequently one can only expect a certain degree of accuracy and it is a waste of time to attempt refinement in field work or reductions that are beyond both the precision of the instruments used and the nature of the element whose weight these instruments are to measure.